

**$g_{KN\Lambda}$  and  $g_{KN\Sigma}$  from QCD sum rules**Seungho Choe<sup>\*</sup>, Myung Ki Cheoun<sup>†</sup>, Su Houn Lee<sup>‡</sup>*Department of Physics**Yonsei University, Seoul 120-749, Korea***Abstract**

$g_{KN\Lambda}$  and  $g_{KN\Sigma}$  are calculated using a QCD sum rule motivated method used by Reinders, Rubinstein and Yazaki to extract Hadron couplings to goldstone bosons. The SU(3) symmetry breaking effects are taken into account by including the contributions from the strange quark mass and assuming different values for the strange and the up down quark condensates. We find  $g_{KN\Lambda}/\sqrt{4\pi} = -1.96$  and  $g_{KN\Sigma}/\sqrt{4\pi} = 0.33$

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## I. INTRODUCTION

Over the years, there has been a continuous interest in the field of kaon-nuclear physics, which range from trying to understand simple processes like the kaon nucleon scattering or the photo-kaon production on a nucleon to the spectroscopy and structure of hypernuclei [1]. Compared to the pions, the conservation of strangeness leads to very different interaction of the Kaons to the nucleon and the nuclei and can therefore yield many exotic states in nuclear physics [1] by either a hadronic or an electromagnetic process.

To understand both these processes and other phenomena in kaon-nuclear physics, it is important to know hadronic coupling strengths involving the kaons. Among them,  $g_{KN\Lambda}$  and  $g_{KN\Sigma}$  are the most relevant coupling constants.

For the pions, their hadronic coupling constant  $g_{\pi NN}$  is determined quite accurately through either the nucleon-nucleon scattering or the pion-nucleon scattering experiment. However, the situation for the kaons are not as satisfactory. For example, to theoretically reproduce the experimental kaon-nucleon scattering cross-section, one usually calculates the contributions from the one-boson exchanges, the resonances in the s-channel, such as the  $\Lambda$  and  $\Sigma$ , and the next to leading two meson exchanges [2]. These involves many phenomenologically undetermined coupling constants so that it seems a formidable task to determine the coupling constants related to the kaons separately.

As another approach, there have been many attempts [2–6] to determine these coupling constants from the kaon photo production. For instance Adelseck *et al.* [3,4] tried to determine these coupling constants( $g_{KN\Lambda}$  and  $g_{KN\Sigma}$ ) phenomenologically from the data using a least-square fit method similar to that of Thom's [5] and deduced some values. But due to the simultaneous determination of many other unknown coupling constants, these results turned out to have large uncertainties, i.e. their extracted values of  $g_{KN\Lambda}/\sqrt{4\pi}$  range from - 1.29 to - 4.17. Hence, given the uncertainties and difficulties in extracting the strength of these couplings from the experiments, it is necessary to explore theoretical predictions.

In this paper, we will use QCD sum rules [7] to extract these kaon couplings. QCD

sum rule is an attempt to understand hadronic parameters in the low energy region in terms of QCD perturbation theory and non-vanishing condensate, which characterizes the non-perturbative QCD vacuum. This is possible by looking at the correlation function between either two or three QCD hadronic currents and studying its dispersion relation, the *Real* part of which is calculated in QCD using the Operator Product Expansion (OPE) and the *Imaginary* part is modeled with the phenomenological parameters. This method has been applied successfully to the pseudo-scalar hadron hadron trilinear couplings by Reinders, Rubinstein and Yazaki [8], who obtained interesting formulas such as,  $g_{\pi NN}^2/4\pi \simeq 2^5\pi^3 f_\pi^2/M_N^2$  and  $g_{\omega\rho\pi} \simeq (2/f_\pi)(e/2\sqrt{2})$ , which are numerically in good agreement with the experiment. Here, we will try to generalize the method to the kaons and hypernucleons. The generalization can be made either within the SU(3) symmetry or with the explicit SU(3) symmetry breaking effects included. The former case has already been given in Ref. [8] and amounts to calculating the F to D ratio [9] in QCD sum rule within the SU(3) symmetry. The SU(3) symmetry breaking effects in QCD sum rules are taken into account by including the effects of strange quark mass and different values for the strange quark condensate  $\langle 0|\bar{s}s|0\rangle = 0.8\langle 0|\bar{u}u|0\rangle$ . This prescription give good description for the  $\phi$  and  $K^*$  meson masses and their couplings [10].

In the following sections, we will derive the QCD sum rule result for the kaon couplings with explicit symmetry breaking and compare the numerical estimates with the results from phenomenological fitting analyses [11–14] and that of other QCD inspired model calculations [15,16].

## II. QCD SUM RULES FOR $G_{K\Lambda}$

We will closely follow the procedures given in Ref. [8]. Consider the three point function constructed of the two baryon currents  $\eta_B$ ,  $\eta_{B'}$  and the pseudoscalar meson current  $j_5$  (Fig. 1)

$$A(p, p', q) = \int dx dy \langle 0|T(\eta_{B'}(x)j_5(y)\bar{\eta}_B(0))|0\rangle e^{i(p'\cdot x - q\cdot y)}, \quad (1)$$

In order to obtain  $g_{KN\Lambda}$ , we will use the following extrapolating fields for the nucleon and the  $\Lambda$ .

$$\eta_N = \epsilon_{abc}(u_a^T C \gamma_\mu u_b) \gamma_5 \gamma^\mu d_c, \quad (2)$$

$$\eta_\Lambda = \sqrt{\frac{2}{3}} \epsilon_{abc} \left[ (u_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu d_c - (d_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu u_c \right], \quad (3)$$

where  $u$  and  $d$  are the up and down quark fields ( $a, b$  and  $c$  are color indices),  $T$  denotes the transpose in Dirac space, and  $C$  is the charge conjugation matrix. For the  $K^-$  we choose the current

$$j_{K^-} = \bar{s} i \gamma_5 u. \quad (4)$$

Assuming a pseudo-vector coupling between the nucleon, the  $K$  and the  $\Lambda$ , we expect the following phenomenological form for Eq.(1).

$$\lambda_N \lambda_\Lambda \frac{M_B}{(p^2 - M_N^2)(p'^2 - M_\Lambda^2)} (\not{q} i \gamma_5) g_{KN\Lambda} \frac{1}{q^2 - m_K^2} \frac{f_K m_K^2}{2m_q}, \quad (5)$$

where  $M_B = \frac{1}{2}(M_N + M_\Lambda)$ ,  $\lambda_N$  and  $\lambda_\Lambda$  are the couplings of the baryons to their currents.  $m_q$  is the average of the quark masses,  $f_K$  is the kaon decay constant and  $m_K$  the kaon mass.  $M_N$  and  $M_\Lambda$  are the masses of the nucleon and the  $\Lambda$  particle respectively. There are other contributions from excited baryon states that couple to the baryon extrapolating current. However, we will only look at the pole structure  $\not{q}/q^2$  at  $q \rightarrow 0$  and make a borel transformation to both  $p^2, p'^2 \rightarrow M^2$ . Then, the contributions from the excited baryons will be exponentially suppressed and consequently neglected in our approximation [10].

As for the OPE side, the perturbative part does not contribute to the  $\not{q}/q^2$  structure. This is so because the dimension of Eq.(1) is 4 and  $\not{q}$  takes away one dimension such that only the odd dimensional operators can contribute. The lowest dimensional operator with dimension 3 is the quark condensate term with higher dimensional operators having the form of a quark condensate with certain number of gluon operators in between. In fact, for the case of the pions, taking into account only the leading quark condensate  $\langle 0 | \bar{q} q | 0 \rangle$  in

the OPE, gives an excellent value for  $g_{\pi NN}$  [10]. Motivated by this result, we will work out similar leading quark condensate contribution as in the pion, which in this case includes the contribution from  $\langle 0|\bar{s}s|0\rangle$ , and further work out the additional SU(3) breaking terms up to  $\mathcal{O}(m_s^2)$  and dimension 7.

First, we will include the contribution proportional to the  $m_s^2$  in the Wilson coefficient of the quark condensate. This will have the following form,

$$A(p, p', q) = C_u \langle 0|\bar{u}u|0\rangle + C_d \langle 0|\bar{d}d|0\rangle + C_s \langle 0|\bar{s}s|0\rangle + \dots \quad (6)$$

One can easily show that  $C_d = 0$  and

$$C_u = -\sqrt{\frac{2}{3}} \frac{11p^2}{24\pi^2} \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p^2}, \quad (7)$$

$$C_s = -\sqrt{\frac{2}{3}} \left( \frac{11p'^2}{24\pi^2} + \frac{11m_s^2}{48\pi^2} \right) \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p'^2}, \quad (8)$$

where  $\Lambda$  is the cut-off from the loop integration. Taking the limit  $p'^2 \rightarrow p^2$  and assuming  $\langle 0|\bar{u}u|0\rangle = \langle 0|\bar{d}d|0\rangle = \langle 0|\bar{q}q|0\rangle$  and  $\langle 0|\bar{s}s|0\rangle = 0.8 \langle 0|\bar{q}q|0\rangle$  we obtain,

$$C_u \langle 0|\bar{u}u|0\rangle + C_s \langle 0|\bar{s}s|0\rangle = -\sqrt{\frac{2}{3}} \left( \frac{33p^2}{40\pi^2} + \frac{11m_s^2}{60\pi^2} \right) \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p^2} \langle 0|\bar{q}q|0\rangle, \quad (9)$$

Next, we consider the lowest order terms that are proportional to the strange quark mass  $m_s$ , namely the dimension 7 operators of the type  $\sim m_s \langle 0|\bar{s}s|0\rangle \langle 0|\bar{q}q|0\rangle$ . The largest contribution among them comes from the tree graph of Fig.2, which gives the following contribution.

$$+ \sqrt{\frac{2}{3}} \frac{m_s}{3} \frac{\not{q}}{q^2} (i\gamma_5) \frac{1}{p^2} \langle 0|\bar{s}s|0\rangle \langle 0|\bar{q}q|0\rangle. \quad (10)$$

After the borel transformation the typical ratio between the contribution from Eq.(10) to Eq.(9) is  $4\pi^2 \cdot m_s \langle 0|\bar{q}q|0\rangle / m_N^4$  for the relevant borel mass range  $M^2 \sim m_N^2$ . The factor of  $4\pi^2$  originates from the fact that Eq.(9) comes from a loop graph whereas Eq.(10) does not. Despite of this loop factors, the additional condensate effect suppresses the overall ratio to less than 5%. Other dimensional 7 operators come from graphs which contain at least one loop and then the ratio to Eq.(9) becomes even smaller and can be neglected.

Using Eq.(9) and Eq.(10) for the OPE and Eq.(5) for the phenomenological side, the sum rule after borel transformation to  $p^2 = p'^2$  becomes,

$$\lambda_N \lambda_\Lambda \frac{M_B}{M_\Lambda^2 - M_N^2} \left( e^{-M_N^2/M^2} - e^{-M_\Lambda^2/M^2} \right) g_{KN\Lambda} \frac{f_K m_K^2}{2m_q} = - \sqrt{\frac{2}{3}} \left( \frac{33}{40\pi^2} M^4 + \frac{11m_s^2}{60\pi^2} M^2 + \frac{m_s}{3} \langle 0 | \bar{s}s | 0 \rangle \right) \langle 0 | \bar{q}q | 0 \rangle. \quad (11)$$

For  $\lambda_N$  and  $\lambda_\Lambda$ , we use the values obtained from the following baryon sum rules for the  $N$  and the  $\Lambda$  [10]:

$$M^6 + bM^2 + \frac{4}{3}a^2 = 2(2\pi)^4 \lambda_N^2 e^{-M_N^2/M^2} \quad (12)$$

$$M^6 + \frac{2}{3}am_s(1 - 3\gamma)M^2 + bM^2 + \frac{4}{9}a^2(3 + 4\gamma) = 2(2\pi)^4 \lambda_\Lambda^2 e^{-M_\Lambda^2/M^2} \quad (13)$$

Here,  $a \equiv - (2\pi)^2 \langle 0 | \bar{q}q | 0 \rangle \simeq 0.5 \text{ GeV}^3$ ,  $b \equiv \pi^2 \langle 0 | (\alpha_s/\pi) G^2 | 0 \rangle \simeq 0.17 \text{ GeV}^4$ , and  $\gamma \equiv \langle 0 | \bar{s}s | 0 \rangle / \langle 0 | \bar{q}q | 0 \rangle - 1 \simeq -0.2$ . We take the strange quark mass  $m_s = 150 \text{ MeV}$ .

It should be noted from Eqs. (12) and (13) that we can not determine the sign of  $\lambda_N$  and  $\lambda_\Lambda$ . Consequently, we can only determine the absolute value of  $g_{KN\Lambda}$  from our sum rules. The sum rule in Eq.(11) should be used for the relevant borel mass  $M \simeq M_B = \frac{1}{2}(M_N + M_\Lambda)$ . Using this we obtain,

$$|g_{KN\Lambda}/\sqrt{4\pi}| \simeq 1.96, \quad (14)$$

A more detailed Borel analysis of Eq.(11) gives a similar result with  $\pm 30\%$  uncertainty. The uncertainty quoted here comes from neglecting the continuum contribution in the phenomenological side.

### III. QCD SUM RULES FOR $G_{KN\Sigma}$

The current of  $\Sigma^\circ$  is defined by [17,18]

$$\begin{aligned}
\eta_{\Sigma^0} &= \frac{1}{\sqrt{2}} \epsilon_{abc} \left[ (u_a^T C \gamma_\mu d_b) \gamma_5 \gamma^\mu s_c + (d_a^T C \gamma_\mu u_b) \gamma_5 \gamma^\mu s_c \right], \\
&= \sqrt{2} \epsilon_{abc} \left[ (u_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu d_c + (d_a^T C \gamma_\mu s_b) \gamma_5 \gamma^\mu u_c \right].
\end{aligned} \tag{15}$$

The second form is more useful in our calculation. Then, within the same approximation as before, the OPE side looks as follows:

$$C_u \langle 0 | \bar{u}u | 0 \rangle + C_s \langle 0 | \bar{s}s | 0 \rangle = + \sqrt{2} \left( \frac{3p^2}{40\pi^2} + \frac{m_s^2}{60\pi^2} \right) \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p^2} \langle 0 | \bar{q}q | 0 \rangle. \tag{16}$$

In this case there is no term like  $\sim m_s \langle 0 | \bar{s}s | 0 \rangle \langle 0 | \bar{q}q | 0 \rangle$ . This is so because the contribution of this form coming from the first term in Eq.(15) cancels that coming from the second term. As can be seen from comparing Eq. (9) to Eq.(16), the ratio between the leading term and the correction proportional to  $m_s^2$  are the same for both cases.

Using a similar form in the phenomenological side as in Eq.(5), the sum rule looks as follows.

$$\begin{aligned}
\lambda_N \lambda_\Sigma \frac{M_B}{M_\Sigma^2 - M_N^2} \left( e^{-M_N^2/M^2} - e^{-M_\Sigma^2/M^2} \right) g_{KN\Sigma} \frac{f_K m_K^2}{2m_q} = \\
+ \sqrt{2} \left( \frac{3}{40\pi^2} M^4 + \frac{m_s^2}{60\pi^2} M^2 \right) \langle 0 | \bar{q}q | 0 \rangle.
\end{aligned} \tag{17}$$

Again for  $\lambda_{\Sigma^0}$ , we take the value from the following sum rule for the  $\Sigma$  [10]:

$$M^6 - 2am_s(1 + \gamma)M^2 + bM^2 + \frac{4}{3}a^2 = 2(2\pi)^4 \lambda_\Sigma^2 e^{-M_\Sigma^2/M^2}. \tag{18}$$

Within the same approximation as before, we take  $M \simeq M_B = \frac{1}{2}(M_N + M_{\Sigma^0})$  in Eq.(17). This gives the following value for the coupling.

$$|g_{K^-N\Sigma^0}/\sqrt{4\pi}| \simeq 0.33. \tag{19}$$

In our approximation, we have SU(2) symmetry; i.e. we neglected the up and down quark masses, and assumed  $\langle 0 | \bar{u}u | 0 \rangle = \langle 0 | \bar{d}d | 0 \rangle$ . Consequently, we can obtain  $g_{KN\Sigma}$  using  $\eta_{\Sigma^+}$  and  $j_{\bar{K}^0}$ , where

$$\eta_{\Sigma^+} = \epsilon_{abc} (u_a^T C \gamma_\mu u_b) \gamma_5 \gamma^\mu s_c, \tag{20}$$

$$j_{\bar{K}^0} = \bar{s}i\gamma_5 d. \quad (21)$$

In this case,  $C_u=0$  and

$$C_d = \frac{p^2}{12\pi^2} \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p^2}, \quad (22)$$

$$C_s = \left( \frac{p'^2}{12\pi^2} + \frac{m_s^2}{24\pi^2} \right) \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p'^2}. \quad (23)$$

Then the final expression in the OPE side is

$$C_d \langle 0 | \bar{d}d | 0 \rangle + C_s \langle 0 | \bar{s}s | 0 \rangle = + \left( \frac{3p^2}{20\pi^2} + \frac{m_s^2}{30\pi^2} \right) \frac{\not{q}}{q^2} (i\gamma_5) \ln \frac{\Lambda^2}{-p^2} \langle 0 | \bar{q}q | 0 \rangle. \quad (24)$$

Again, there is no term proportional to  $\sim m_s \langle 0 | \bar{s}s | 0 \rangle \langle 0 | \bar{q}q | 0 \rangle$ . Neglecting the difference between  $M_{\Sigma^0}$  and  $M_{\Sigma^+}$  in the phenomenological side, and comparing Eq. (24) with Eq. (16) we obtain the well known relation from isospin symmetry,

$$g_{K^- N \Sigma^0} = \frac{1}{\sqrt{2}} g_{\bar{K}^0 N \Sigma^+}. \quad (25)$$

Because the contribution of each coefficient is the same, we obtain this relation despite of taking  $\langle 0 | \bar{s}s | 0 \rangle = 0.8 \langle 0 | \bar{q}q | 0 \rangle$  and including the strange quark mass correction. This reflects the SU(2) symmetry within our approach. (see Eqs. (7), (8) and Eqs. (22), (23)).

#### IV. DISCUSSION

The SU(3) symmetry, using de Swart's convention, predicts

$$\begin{aligned} g_{KN\Lambda} &= - \frac{1}{\sqrt{3}} (3 - 2\alpha_D) g_{\pi NN} \\ g_{KN\Sigma} &= + (2\alpha_D - 1) g_{\pi NN} \end{aligned} \quad (26)$$

where  $\alpha_D$  is the fraction of the D type coupling,  $\alpha_D = \frac{D}{D+F}$ . Using the expression of  $g_{\pi NN}$  in Ref. [8] and comparing the OPE sides only, we obtain  $\alpha_D = 7/12$  in the SU(3) symmetric limit. This limit is denoted by QSR I in table I.



Our case(denoted by QSR II in table I) does not satisfy Eq. (26) because of the additional SU(3) symmetry breaking factors in the OPE and in the phenomenological side. Using the convention by de Swart<sup>1</sup> we get

$$\begin{aligned} g_{KN\Lambda}/\sqrt{4\pi} &= -1.96, \\ g_{KN\Sigma}/\sqrt{4\pi} &= +0.33. \end{aligned} \tag{27}$$

Comparing QSR I and QSR II, we note that the SU(3) symmetry breaking effect for the couplings are in the order of 25 ~ 30 %. This order is similar to the SU(3) symmetry breaking effects observed in the vector meson masses or the square of the couplings to the electro-magnetic current.

In Ref. [4] the ranges for the coupling constants are given by fitting  $g_{\pi NN}$  and  $\alpha_D$  to experimental data and allowing for SU(3) symmetry breaking at the 20 % level. This gives the following range:

$$\begin{aligned} g_{KN\Lambda}/\sqrt{4\pi} &= -4.4 \text{ to } -3.0, \\ g_{KN\Sigma}/\sqrt{4\pi} &= +0.9 \text{ to } +1.3. \end{aligned} \tag{28}$$

Other experimentally extracted values, which are summarized as I, II and III in table I, lie within the limits above, except for the case denoted by IV.

Comparing these limits with our QSR calculations, we observe that our values fall short of the experimental limits, although it is closer than the predictions of the Skyrme model. However, it should be noted that the present experimental extraction of the couplings involve a simultaneous determinations of many other unknown parameters and a model dependent subprocesses. Therefore it is necessary to investigate the problem further both theoretically and experimentally.

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<sup>1</sup>In fact, there is another convention [4,19].

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## TABLES

Table I. Coupling constants,  $g_{KN\Lambda}$  and  $g_{KN\Sigma}$ . Set I and II are the results from an analyses of the kaon - nucleon scattering. Set III is the result of Adelseck and Saghai from the analysis of the photo - kaon scattering and set IV is the result of Mart *et al.* from the analysis of the charged  $\Sigma$  photoproduction. SM I and II are the Skyrme Model predictions. QSR I is a QCD sum rule prediction using  $\alpha_D = 7/12$  in the SU(3) symmetric limit. QSR II is our result including the SU(3) symmetry breaking effects.

Coupling Constants	I [11]	II [12]	III [13]	IV [14]	SM I [15]	SM II [16]	QSR I	QSR II
$g_{KN\Lambda}/\sqrt{4\pi}$	3.73 <sup>†</sup>	3.53 <sup>†</sup>	$-4.17 \pm 0.75$	0.510	$-2.17^{\ddagger}$	$-0.67^{\S}$	-2.76	-1.96
$g_{KN\Sigma}/\sqrt{4\pi}$	1.82 <sup>†</sup>	1.53 <sup>†</sup>	$1.18 \pm 0.66$	0.130	0.76 <sup>‡</sup>	0.24 <sup>§</sup>	0.44	0.33

<sup>†</sup> Sign undetermined.

<sup>‡</sup> With  $f_\pi = 54$  MeV,  $e = 4.84$  which give the experimental values of N and  $\Delta$  masses.

<sup>§</sup> With the empirical  $f_\pi = 93.0$  MeV, and  $e = 4.82$  which gives a  $\Delta$  - N mass difference.

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## FIGURES

FIG. 1. The three point function.  $\eta_B, \eta_{B'}$  are the baryon currents and  $j_5$  is the pseudoscalar current.  $\lambda_B$  and  $\lambda_{B'}$  are the couplings of the baryons to the currents, and  $g_{KBB'}$  is the three point coupling.

FIG. 2. Contribution from the strange quark mass and quark condensates. Solid lines are the baryon currents and dashed line is the meson current.

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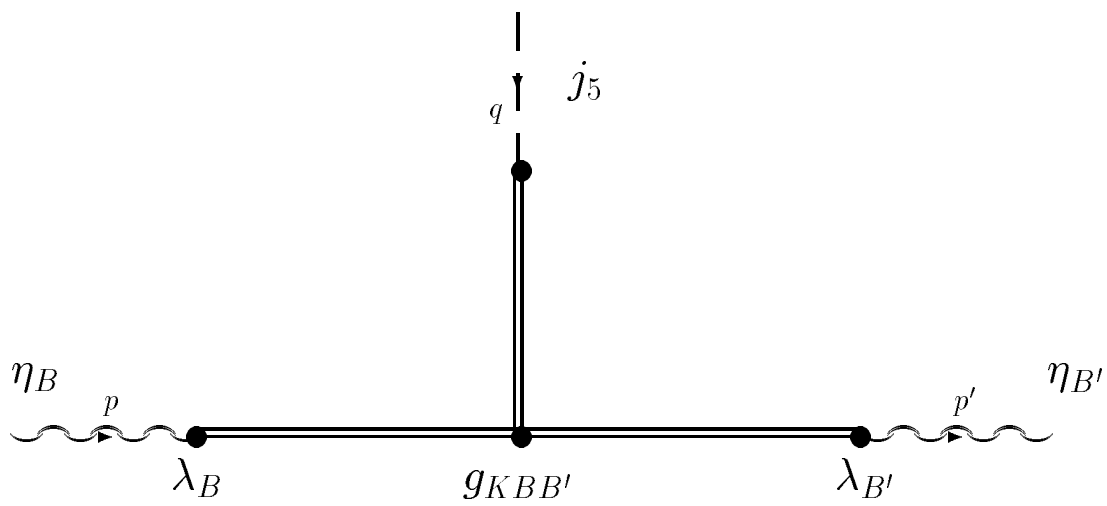


Fig. 1

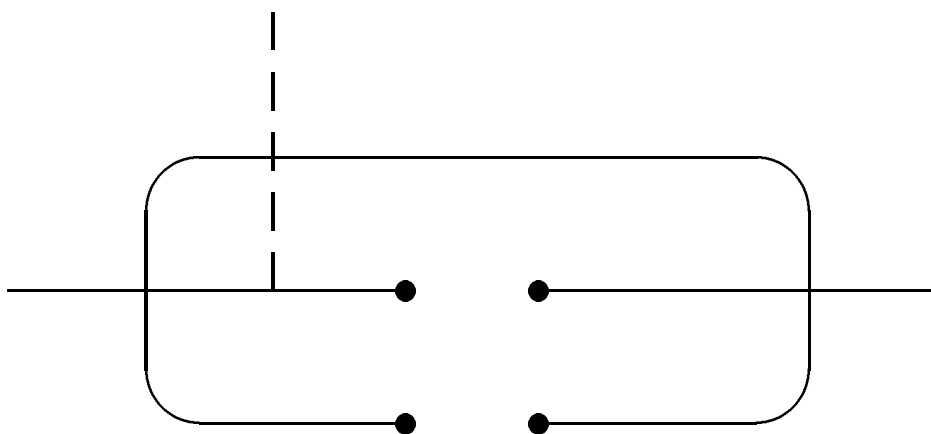


Fig. 2